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(54) **SINGLE PHOTON DETECTION WITH
SELF-QUENCHING MULTIPLICATION**

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H01J 43/04 (2006.01)
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(52) **U.S. Cl.** **250/214.1**; 257/186; 257/438

(58) **Field of Classification Search** 250/214.1;
257/186, 199, 438, 603
See application file for complete search history.

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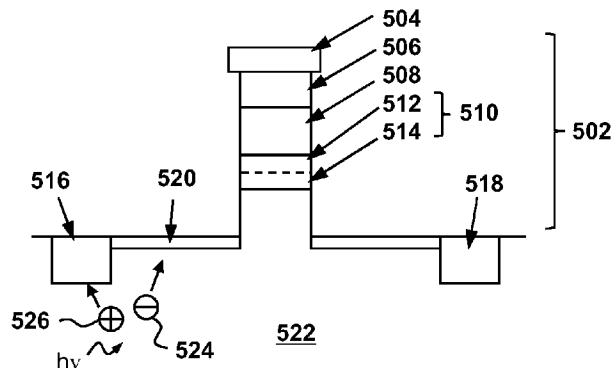
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(57) **ABSTRACT**

A photoelectronic device and an avalanche self-quenching
process for a photoelectronic device are described. The pho-
toelectronic device comprises a nanoscale semiconductor
multiplication region and a nanoscale doped semiconductor
quenching structure including a depletion region and an
undepletion region. The photoelectronic device can act as a
single photon detector or a single carrier multiplier. The ava-
lanche self-quenching process allows electrical field reduc-
tion in the multiplication region by movement of the multi-
plication carriers, thus quenching the avalanche.

20 Claims, 7 Drawing Sheets



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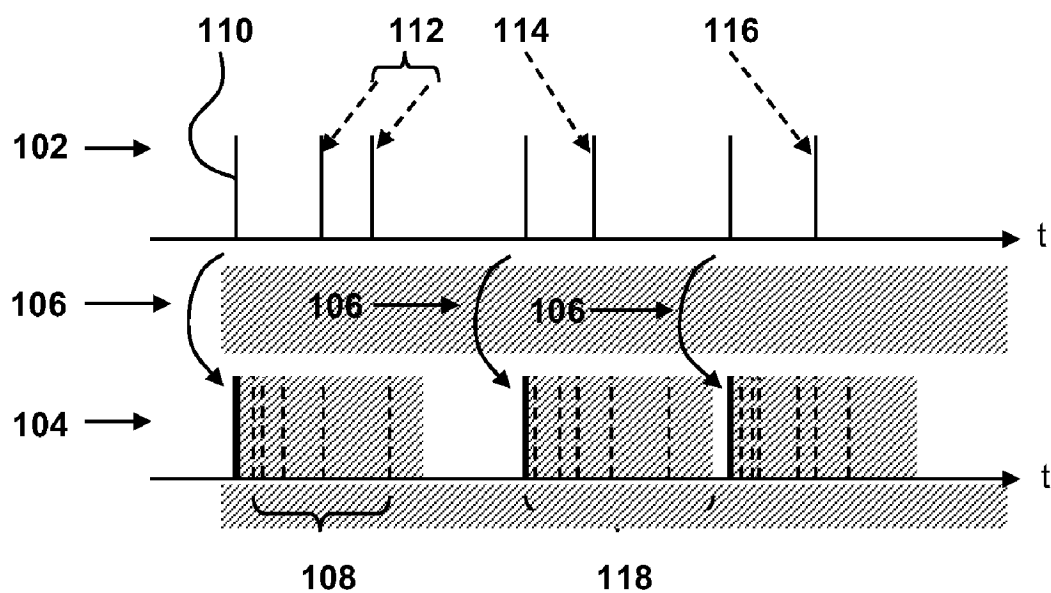


FIG. 1
(Prior Art)

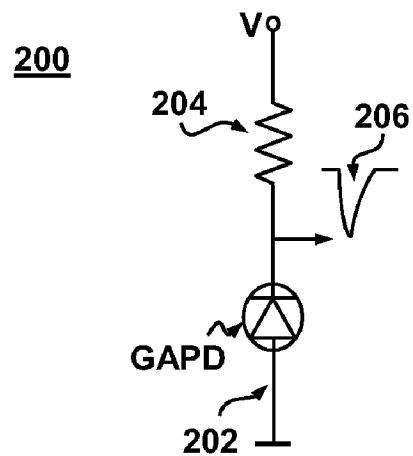


FIG. 2
(Prior Art)

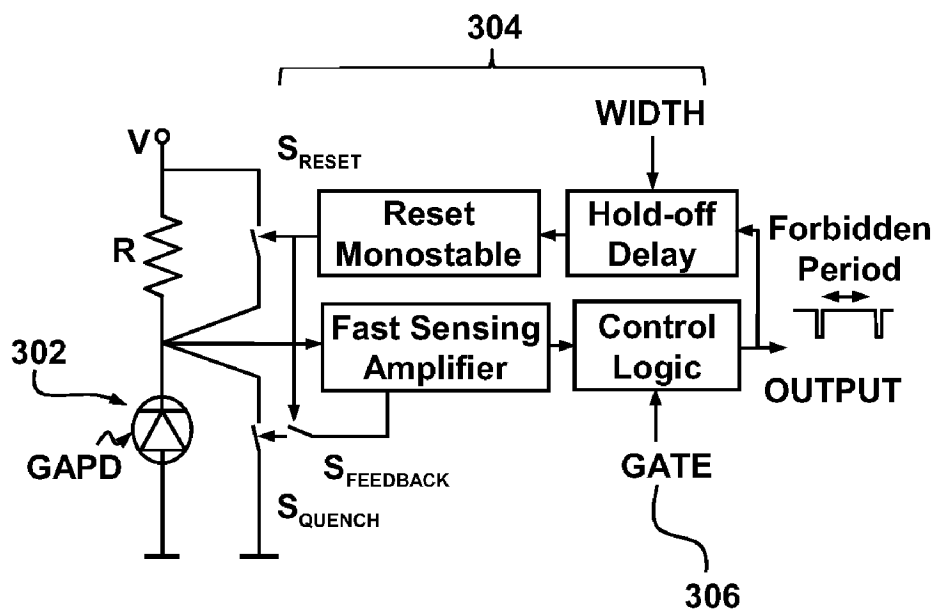


FIG. 3
(Prior Art)

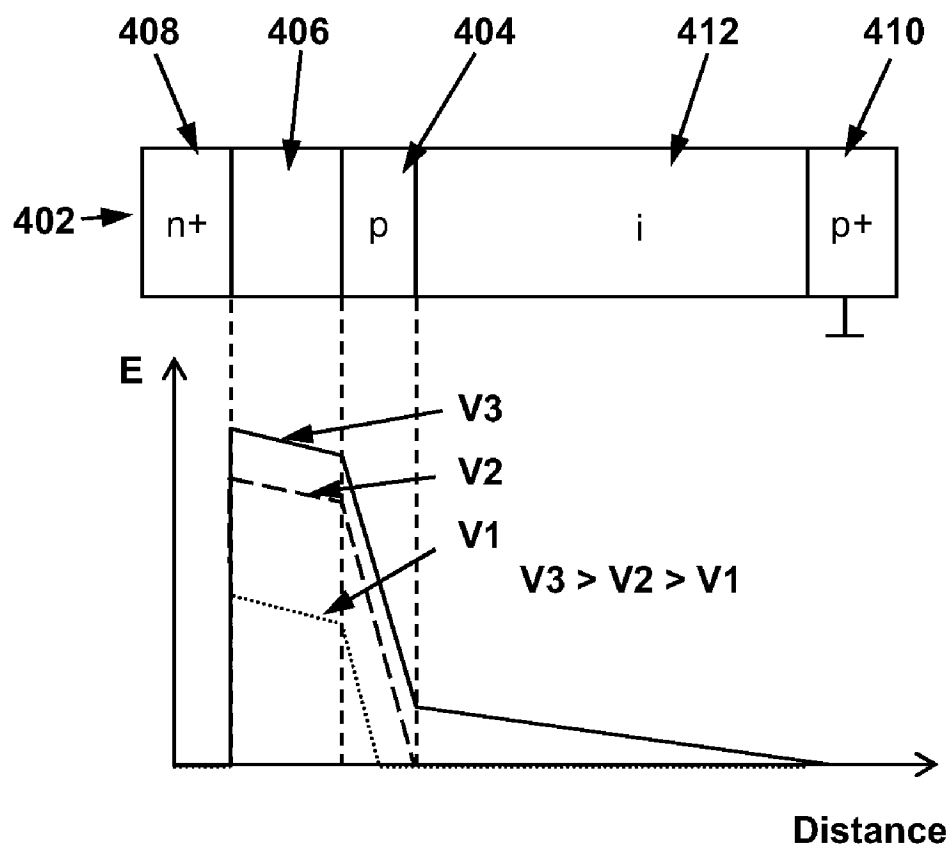
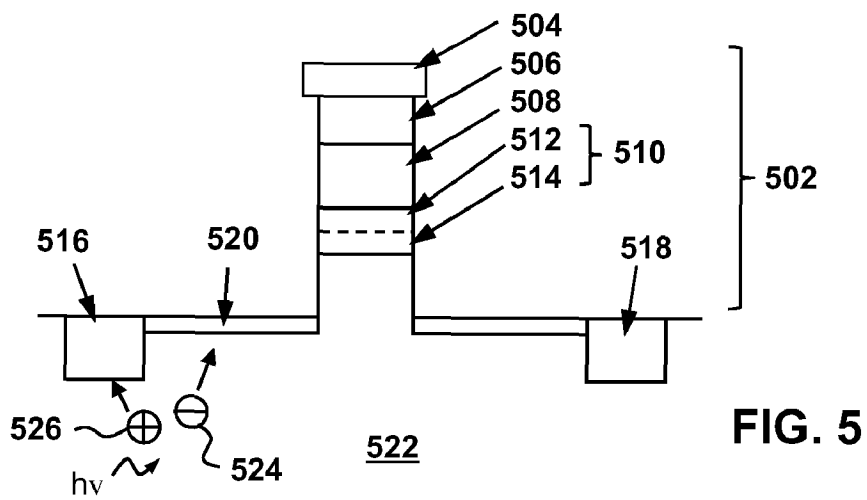
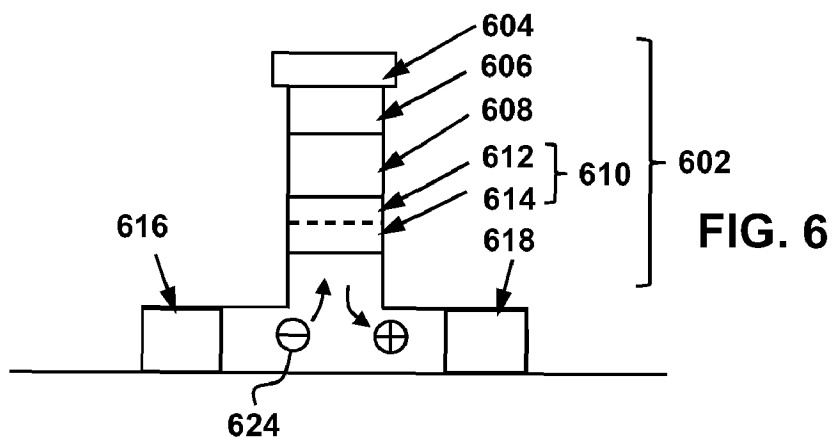
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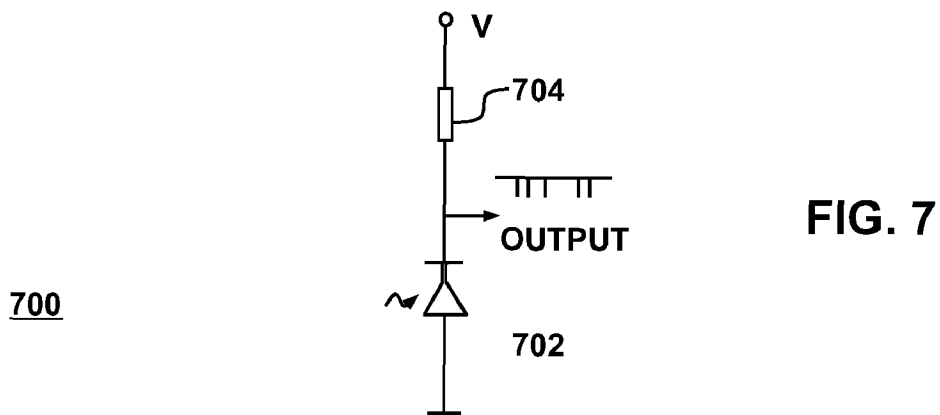
FIG. 4
(Prior Art)



500



600



700

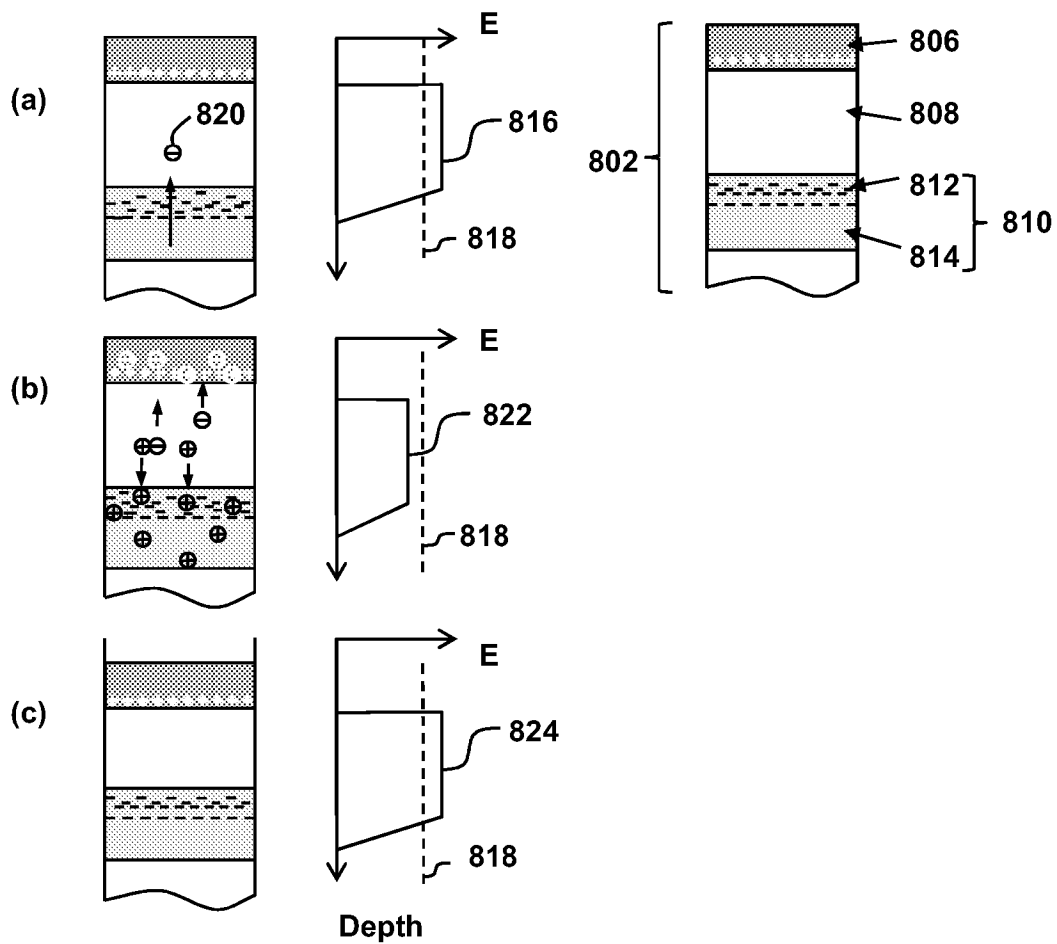


FIG. 8

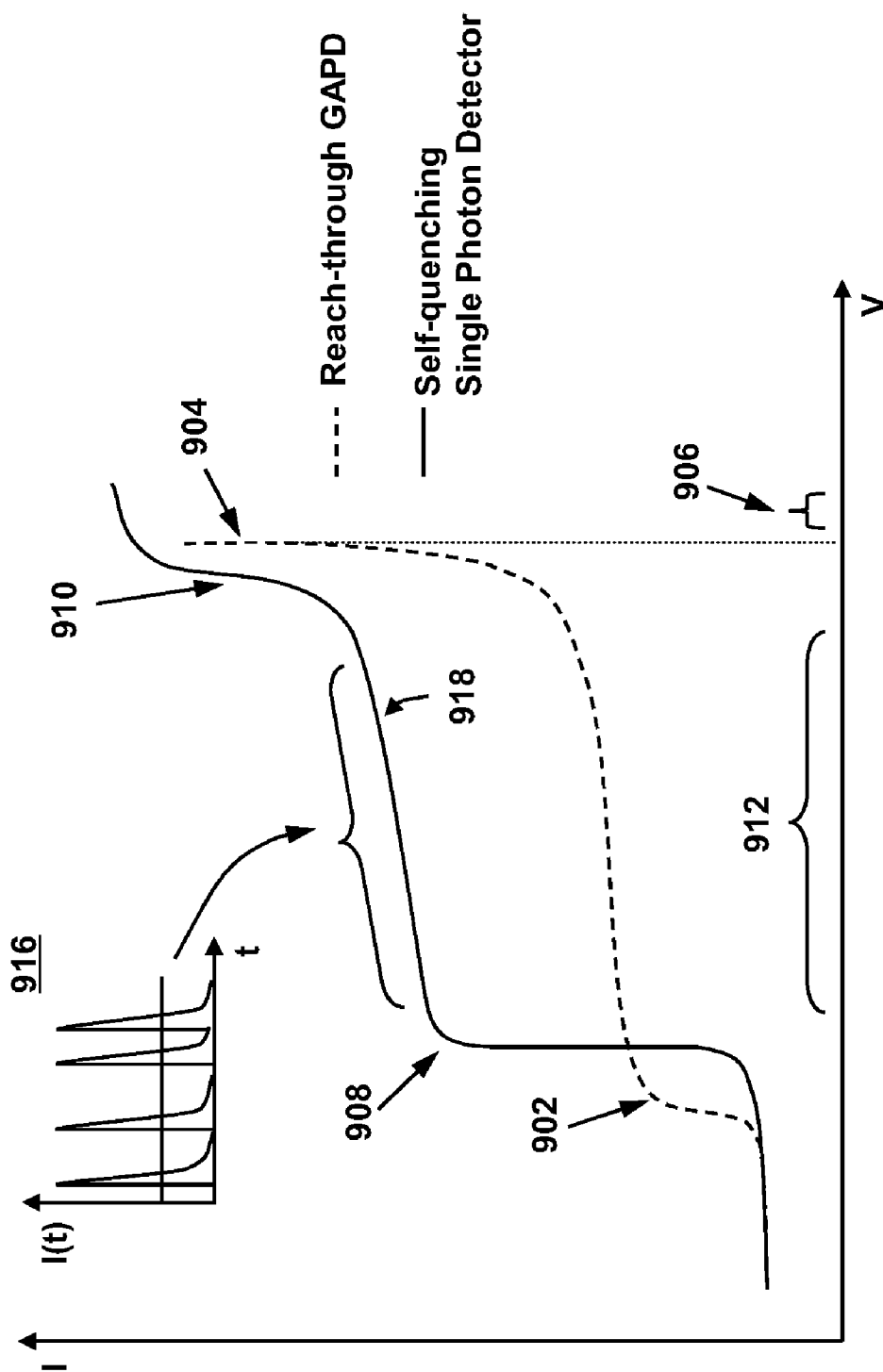
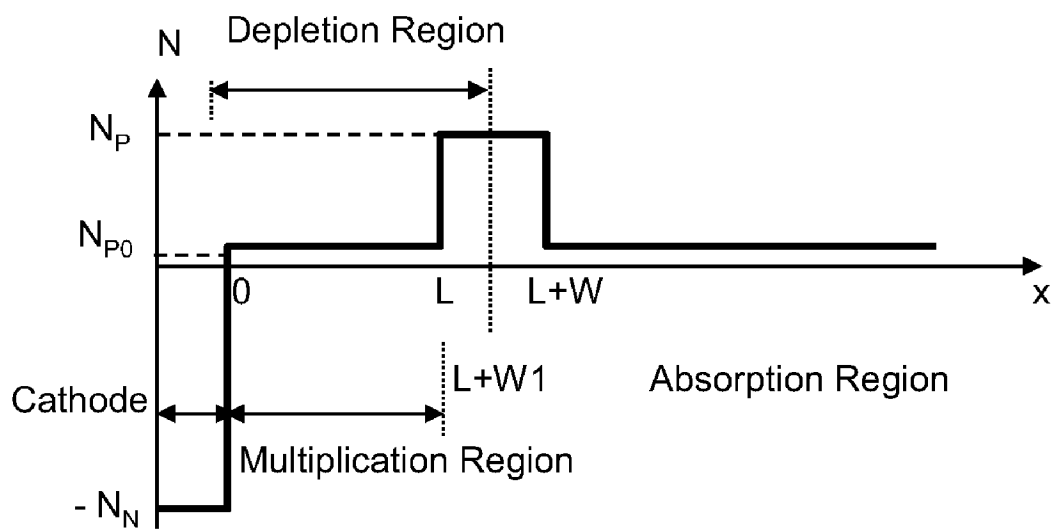


FIG. 9

**FIG. 10**

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SINGLE PHOTON DETECTION WITH SELF-QUENCHING MULTIPLICATION

CROSS REFERENCE TO RELATED APPLICATIONS

The present application is related to and claims the benefit of copending and commonly assigned U.S. Patent Application No. 61/065,696, titled "Self-quenching Single Photon Detector with a Partially Depleted Quenching Layer in a Pillar Structure," filed on Feb. 14, 2008, the entire contents of which are incorporated herein by reference.

STATEMENT OF GOVERNMENT GRANT

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

FIELD

The present disclosure relates to photon detection and multiplication. More in particular, it relates to single photon detection with self-quenching multiplication, such as apparatus and methods for single photon detection with self-quenching multiplication and pulse output.

BACKGROUND

The photomultiplier tube (PMT) has dominated the area of single photon counting and single photon detection for many years. While possessing the desired photon counting functionality, i.e., outputting an explicit pulse upon reception of one single photon, a PMT is substantially bulky because of its vacuum tube nature. Besides, wavelength coverage and quantum efficiency of a PMT are both low. These drawbacks, plus low counting rate, high voltage and limited lifetime, make it impossible or very difficult to employ a PMT in many advanced areas, such as high speed photon counting, photon counting imaging, large format and spatially resolved photon and article detection, and space missions.

Geiger mode avalanche photodiodes (GAPDs) have also been employed for single photon counting. However, two major drawbacks, i.e., low speed/low counting rate and a requirement for external quenching, have severely inhibited advanced applications using Geiger mode avalanche photodiodes.

In particular, afterpulsing is an effect that substantially restrains the photon counting rate of a GAPD. Afterpulsing refers to a series of avalanche events triggered by the carriers that were generated in previous avalanche events, captured by the traps located at the vicinity of the avalanche region and then liberated again by these traps. The probability for afterpulsing to occur after detection of a signal photon is correlated to the amount of the traps located in the high field region and also the excess voltage, i.e., the amount of the bias above the breakdown voltage.

The time period needed for the afterpulsing probability to drop to below an acceptable level, which is known as the deadtime of the photon counting detector, normally ranges between microseconds and milliseconds. In order to prevent the afterpulses from being erroneously counted, photon counting should be blocked for a duration, which is named as reset time, after detection of a signal photon.

The upper portion of FIG. 1 shows a sequence 102 of photons incident into a gated GAPD. The lower portion of

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FIG. 1 shows the photon counting output 104 as a consequence of the photon events counted 106. Since the afterpulsing effect has high probability to occur in a certain time period or deadtime 108 after detection of a photon 110, photon incidence events 112, 114, 116 during the deadtime period are blocked or gated from counting, see reset time 118. As a result, the repeating rate of the photon counting is restricted by the magnitude of the deadtime.

Low avalanche initiation probability (AIP), which is general in GAPDs, leads to low quantum efficiency because the effective quantum efficiency is the product of AIP and the inner quantum efficiency. Avalanche initiation probability refers to the probability of a photoelectron to trigger an avalanche event in a GAPD detector. High avalanche initiation probability needs ideally uniform junction and multiplication region in the GAPD. Any artifacts, which include edge effect, defects and junction curvature, will lead to an "early breakdown" at a specific location and hence significantly reduce the probability for photogenerated carriers at other locations to trigger avalanche events there, leading to low AIP. Moreover, a GAPD pixel in an imaging array will suffer from a more severe AIP problem because its structure has to compromise with the processing technology.

More importantly, a Geiger mode avalanche photodiode (GAPD) requires an external quenching circuit to stop each of the avalanche events occurred inside it for otherwise the device will be burned out by the avalanching current. Because a GAPD pixel will become inactive after capture of one photon and the operation to reset the inactive pixels through the external quenching circuits is slow, a GAPD imager cannot recognize a scene unless the photon flux is very low, leading to a very low dynamic range.

Passive and active quenching are the two quenching techniques currently available. Their typical circuits are schematically illustrated in FIG. 2 and FIG. 3. As discussed below, passive quenching is intrinsically slow because of the RC effect originated from the required high value of the quenching resistor. On the other hand, in view of chip area and power consumption requirements, active quenching does not suit array applications.

In particular, FIG. 2 shows a traditional Geiger mode Avalanche photodiode (GAPD) 202 in series with a passive quenching resistor 204. Once an avalanche effect occurs in the GAPD device 202, the high value of the resistor 204 will lead to a drop of the voltage across the GAPD 202 to below its breakdown voltage, hence quenching the avalanche process. A possible value for resistor 204 is 100 kΩ. Such high value of the resistor 204 results in a slow quenching process and even slower reset process, as also illustrated by the output waveform 206.

FIG. 3 shows a GAPD 302 with an active quenching circuit 304. While high speed can be achieved with the help of the quenching circuit 304, additional power consumption and space (or chip area, in the case of integrated circuits) will be required to implement this measure. For this reason, active quenching does not suit a GAPD imaging array. To exclude an erroneous counting of pulses resulting from the afterpulsing effect, a gating function 306 is incorporated in the quenching circuit 304 to prevent photon counting for a certain period after a real photon count. This, however, means that the afterpulsing effect will degrade the speed performance of a GAPD, even in the presence of a high speed quenching circuit.

There have been efforts to construct a "solid-state photomultiplier" (Christopher Stapels et al. "Solid-State Photomultiplier in CMOS Technology for Gamma-Ray Detection and Imaging Applications" Nuclear Science Symposium

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So-called "reach-through" structures are also known in the art. FIG. 4 shows the structure (upper portion of the figure) and the electric field bias profiles at different levels (lower portion of the figure) of such reach-through structure. This structure has been widely used in various avalanche photodiodes built on different semiconductor materials.

By inserting a layer 404 of p type reach-through structure beneath a multiplication region 406 in a structure also comprising a cathode 408, an anode 410, and an absorption region 412, high field will be restricted in the multiplication region 406 sandwiched between the cathode 408 and the reach-through structure 404. This will eliminate the probability for an avalanche event to occur outside the multiplication region 406. As the bias increases, the reach-through structure 404 will be fully depleted first and then the depletion region will penetrate into the absorption region 412, followed by breakdown occurring in the multiplication region 406.

The term "nanoscale" is used throughout the present disclosure to describe the lateral structural feature of all the component parts of the device according to the present disclosure that are contained in a pillar structure. In order to reflect the specific dimensional feature of the detector, the implication of the term "nanoscale" through the present disclosure is a little bit different from its usual meaning. In particular, throughout the present disclosure the term "nanoscale" will refer to a dimension ranging from 1-2,000 nm, and a nano-pillar will mean a pillar structure with a "nanoscale" diameter.

SUMMARY

According to a first aspect, a photoelectronic device is provided, comprising: a nanoscale doped semiconductor cathode or anode receiving, during operation of the photoelectronic device, multiplied electrons or holes; an undoped or unintentionally doped nanoscale semiconductor multiplication region connected with the cathode or anode, the multiplication region hosting carrier avalanche and carrier self-quenching during operation of the device; and a nanoscale doped semiconductor quenching structure connected with the multiplication region, the quenching structure comprising a depletion region that undergoes depletion during operation of the device and an undepletion region that remains undepleted during operation of the device.

According to a second aspect, an avalanche and self-quenching process for a photoelectronic device is provided, comprising: providing a nanoscale multiplication region and a nanoscale quenching structure connected with the nanoscale multiplication region, the nanoscale quenching region comprising a depletion layer that undergoes depletion during the avalanche and self-quenching process and an undepletion layer that remains undepleted during the avalanche self-quenching process; and injecting a photoelectron or a photo-generated hole into the nanoscale multiplication region, whereby avalanche is initiated upon the injecting and pairs of free carriers are generated as a result of carrier multiplication, wherein: space charge initially contributed by the depletion layer of the nanoscale quenching region is modulated as multiplied carriers of one type move through the nanoscale quenching structure, and electrical field in the multiplication region is reduced as a result of the modulation, thus quenching the avalanche.

Further aspects of the present disclosure are shown in the specification, drawings and claims of the present application.

According to some embodiments of the present disclosure, the detector of the disclosure is provided with a PMT-like self-quenching ability, a very short deadtime due to significantly eliminated afterpulsing effect and high quantum efficiency enabled by several measures including a favorite structure and a high avalanche initiation probability. The dark current or dark count rate of the detector of this disclosure, though still being larger than that of a PMT, is significantly lower than that of a traditional GAPD.

The teachings of the present disclosure can be applied to the fields of high speed single photon detection and high repeating rate single photon counting (e.g., Gigahertz photon counting optical communication), and high speed and time resolved single photon detection (e.g., various spectrometers and spectroscopy with nanosecond time resolution, including laser Induced Breakdown Spectroscopy, Laser Induced Fluorescence Spectroscopy, Raman Spectroscopy, and interferometer). Other application can include photon counting imaging (e.g., gigabit camera with extra-high dynamic range and extra-high contrast), spatially resolved large area photon detection for high energy physics and medical applications (e.g. Positron Emission Tomography, large area scintillation detector array), and space applications where low voltage, low power, robustness, and compactness are of extreme importance.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a sequence of photons incident into a gated GAPD.

FIG. 2 shows a GAPD in series with a passive quenching resistor.

FIG. 3 shows a GAPD with an active quenching circuit.

FIG. 4 shows a structure and electric field bias profiles at different levels of a reach-through structure.

FIG. 5 shows a first embodiment of the device according to the present disclosure.

FIG. 6 shows a second embodiment of the device according to the present disclosure.

FIG. 7 shows a circuit diagram of the device of the first embodiment according to the present disclosure.

FIG. 8 is a multi-diagram figure showing the avalanche and self-quenching bi-process in the multiplication region of a device according to the present disclosure.

FIG. 9 shows an exemplary I-V curve of the device of the first embodiment according to the present disclosure compared with the I-V curve of a GAPD with a prior art reach-through structure.

FIG. 10 shows doping concentration of a device according to the present disclosure as a function of the distance from the cathode or anode.

DETAILED DESCRIPTION

Because of the quantum nature of a photon, single photon detection is the ultimate photon detection. A single photon usually generates a pair of single carriers (one electron and one hole) in a detector. For this reason, single photon detection can also be deduced to detection of a single carrier. Noise of the readout electronics or amplifiers is the major challenge faced by single photon detection and single carrier detection because the noise is normally equivalent to tens or more electrons. Carrier multiplication can turn one carrier generated by one photon into a big signal comprising tens, hundreds, thousands or even more carriers. While the multiplied

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signal can be directly sense or count explicitly, the multiplication should introduce little noise on its own turn.

FIG. 5 shows a first embodiment of the present disclosure, where a self-quenching single photon detector **500** is represented. Self-quenching single photon detector **500** comprises a stacked doped structure **502** in a vertical pillar.

A nanoscale cathode contact **504** provides ohmic contact to a nanoscale cathode **506** and prevents invasion of metal elements into cathode **506**. Cathode contact **504** can be a layer of amorphous or polycrystalline semiconductor having the same doping type as that of cathode **506**. The thickness of cathode contact **504** can be, for example, in a 50-200 nm range. Cathode **506** is a n^+ type cathode, to which positive voltage will be applied during operation of the self-quenching single photon detector **500**. The thickness of cathode **506** can be, for example, in a 50-200 nm range.

A p^- type multiplication region **508** is an undoped or unintentionally doped layer between the cathode **506** and the later described quenching structure **510**. During operation of the device, an avalanche process or a self-quenching process occur in multiplication region **508**, as later explained. The thickness of multiplication region **508** can be, for example, in 100-500 nm range.

A quenching structure **510** comprises a p type upper portion **512** that will be depleted during operation of the self-quenching single photon detector **500** and a p type lower portion **514** that will stay undepleted during operation of the self-quenching single photon detector **500**. The conditions under which a structure that is to be partially depleted during operation, can be obtained, will be later explained with reference to FIG. 10.

Similar to the reach-through structure previously discussed with reference to FIG. 4, the depleted p type quenching structure **512** leads to concentration of high field in the multiplication region **508**. As to the undepleted portion of the p type quenching structure **514**, because of its presence, the quenching structure **510** is not fully depleted as the multiplication region **508** reaches the breakdown status or goes beyond it, as later explained in better detail with reference to FIG. 10.

The partial depletion of the quenching region **510** (i.e. the undepletion of layer **514**) ensures that the multiplication region or layer **508** enters the status of breakdown at a very low voltage (e.g., 10V or below). Moreover, the undepleted layer **514** forms a shallow quantum or potential well for the holes. This retards the movement of the multiplied holes generated in an avalanche event on their way back to the anode **516, 518** and the positive space charge modulation thus formed will reduce the electrical field strength in the multiplication region down to below the critical value for breakdown. Therefore, the avalanche will be quenched.

The thickness of the quenching structure **510** comprised of depleted layer **512** and undepleted layer **514** can be, for example, between 100 and 500 nm.

The nanoscale diameter of the pillar is advantageous to the occurrence of the self-quenching effect because a large diameter may allow lateral spreading of the multiplied holes, hence weakening or even disabling the self-quenching effect. On the other hand, a nanoscale pillar structure **502** provides benefits that include significantly lowered dark current or dark count rate, virtual elimination of the afterpulsing effect, largely increased avalanche initiation probability and, most importantly, very high speed and very high photon counting rate. According to an embodiment of the present disclosure, the height of pillar structure **502** is, for example, between 300 nm and 1,500 nm and its diameter is, for example, between 10 nm and a couple of microns.

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With continued reference to FIG. 5, the self-quenching single photon detector **500** comprises an n type floating cathode **520** formed on a shoulder region of the self-quenching single photon detector **500** to help development of depletion into an absorption region **522** and collection of photoelectrons from the absorption region **522**. With the floating cathode **520**, the lateral dimension of the detector can be extended up to a range between, for example, 100 and 1000 μm .

Region **522** is an i type or p^- type absorption region, i.e. a low doping region for photons incident from the front or back side. The photoelectrons **524** will be collected to the floating cathode **520** and then guided to the pillar **502**. On the other hand, the holes **526** photo-generated in the absorption region **522** will flow back to the anode **516, 518** together with the multiplied holes coming from the pillar **502**.

FIG. 6 shows a second embodiment of the present disclosure, where a self-quenching single electron multiplier **600** is shown. Such second embodiment is useful in situations where a carrier multiplication region cannot be easily built on the same material of the detector.

Similarly to the embodiment of FIG. 5, the embodiment of FIG. 6 shows a pillar **602** comprising a cathode contact **604**, an n^+ type cathode **606**, a p^- type multiplication region **608**, a p type quenching structure **610** which comprises, in turn, a depleted quench layer **612** and an undepleted quench layer **614**.

Differently from the embodiment of FIG. 5, the embodiment of FIG. 6 does not absorb photons itself, but converts single electrons **624** from another detector into a pulse output of device **600**. Therefore, device **600** does not contain an absorption region and contains instead an n^+ type contact **616** as an inlet for electrons coming from other detectors or devices. Device **600** also includes a p^+ type anode **618**.

Therefore, as shown in FIG. 5 and FIG. 6, the doped structure **502/602** can serve either as a self quenching single photon detector **500** by combining structure **502** with a photon absorption region **522** to convert incident photons into outputted pulses, or as a self quenching single electron multiplier **600** to convert electrons collected from other detectors or devices into pulses. The single electron multiplier embodiment can be used in situations where the carrier multiplication region cannot be easily fabricated on the same material of the detector.

Although vertical pillars or vertically aligned structures have been described with reference to FIG. 5 and FIG. 6, the person skilled in the art will understand, upon reading of the above paragraphs, that also horizontally aligned (or differently aligned) doped structures can be provided. Moreover, although silicon can be the semiconductor material of choice, other semiconductor materials can also be used with the teachings of the present disclosure. Still further, inverted structures (where hole multiplication replaces electron multiplication) can be provided, with polarities opposite to those shown in FIG. 5 and FIG. 6.

FIG. 7 is a circuit diagram **700** showing the detector **702** according to the present disclosure. The resistor **704** in series with detector **702** is inserted simply for sensing the pulse current passing through the detector **702** so its value can be very low if needed.

FIG. 8 is a multi-diagram figure showing the avalanche and self-quenching process in the multiplication region of a self-quenching single photon detector or a self-quenching single electron multiplier. The right portion of FIG. 8 is a schematic representation of a structure **802** comprising a cathode **806**, a multiplication region **808**, and a quenching structure **810**

inclusive of a depleted layer **812** and an undepleted layer **814**. Positive and negative space charges are represented with “+” and “-”, respectively.

Insets (a), (b) and (c) of FIG. **8** show the changes occurring in the structure **802** during the avalanche and self-quenching processes, together with the values of the electric field *E* as a function of the depth of the structure.

As shown in inset (a), the field **816** in the multiplication region exceeds the critical value, indicated by dashed line **818**, for occurrence of breakdown. Even with a field exceeding the limit, the breakdown does not occur until a photoelectron **820** injects into the multiplication region **808**.

Turning now to inset (b), the avalanche initiated by the injection of photoelectron **820** is shown. Electrons and holes are generated as a result of carrier multiplication. Since the partially depleted quenching structure **810** forms a potential well for holes, the movement of the multiplied holes across the undepleted quenching region **814** is retarded, thus causing piling up of additional positive space charges in the quenching structure. The spontaneous space charge moderation thereafter caused leads to reduction of the multiplication field down to a value **822** below the critical value **818** for breakdown. Therefore, the avalanche is quenched because of the reduced field.

After sweeping out of the residual free carriers in the structure, the situation shown in inset (c) is now reached, where there are no more free electrons or holes in the multiplication region **808**. Because of the elimination of the additional space charge, the field in the multiplication region **808** returns to a value **824** above the critical value **818**, waiting for injection of the next photoelectron.

Therefore, as shown in FIG. **8** and described above, the partially depleted doped layer **810** beneath the multiplication region **808** plays an important role in the device according to the present disclosure. Because the field *E* in the multiplication region **808** is enclosed by the quenching structure **810**, a low voltage (as low as 10V, as mentioned above) can lead to breakdown in the multiplication region **808**, as discussed with reference to inset (b) of FIG. **8**. On the other hand, the multiplied holes generated in an avalanche process have to flow across the quenching layer **810** (downward direction in the representation of FIG. **8**) on their way back to the anode (see, e.g., anodes **516**, **518** of FIG. **5**). Presence of these holes in the quenching layer **810** will lead to the spontaneous reduction of the negative space charges intrinsically existing in the depleted portion **812** of the quenching layer **810**. Compensation or feedback will be enhanced by two factors. First, the undepleted portion **814** of the quenching structure **810** forms a potential well which will retard movement of the multiplied holes. Secondly, the nanoscale dimension of the pillar structure **802** allows confinement of the multiplied holes and maximization of the feedback effect. As a result, the field in the multiplication region **808** will be reduced to a value below the critical value for breakdown, thus quenching the ongoing avalanche process.

With such an interaction between avalanche and self-quenching, the average voltage dropped across the multiplication region **808** will keep substantially constant. Except for a value that drops across the multiplication region **808**, the excess voltage will drop across the absorption region (see, e.g., region **522** of FIG. **5**), resulting in depletion there. Further increase of the bias will lead to occurrence of breakdown in the absorption region. According to an experimental veri-

fication made by applicants, the workable bias for a self-quenching single photon detector is between 10V and 40V. By way of comparison, a typical bias range for a GAPD is about 5V to 10V beyond a breakdown voltage of, typically, 100V.

FIG. **9** shows an exemplary I-V curve of the self-quenching single photon detector according to the present disclosure (solid line) compared with the I-V curve of a GAPD with a prior art reach-through structure (dashed line). The curve of the reach-through GAPD first attains a status of “reach-through”, indicated by a small plateau **902**, and then gradually develops into breakdown **904**. The small bias range **906** above the breakdown voltage is the applicable bias range for Geiger mode operation.

Although the curve of the self-quenching single photon detector according to the present disclosure has a similar shape, its mechanism is different from that of a reach-through GAPD. The first rising region **908** of the self-quenching single photon detector curve indicates establishment of breakdown status in the multiplication region (see regions **508**, **608** and **808** of respective FIGS. **5**, **6** and **9**). The second rising region **910** represents breakdown in the absorption region (see region **522** of FIG. **5**). The large bias range **912** between the two raising segments **908**, **910** is a working bias range of the self-quenching single photon detector. Because of the balanced interactions between the avalanche and self-quenching processes, the average voltage dropped across the multiplication region will be kept virtually constant. The excess voltage will drop across the absorption region and hence deplete it as the bias goes up from the first breakdown. Also shown in FIG. **9** are a pulsed current **916** which represents the transient current passing through the detector and the apparent DC current **918**, which is an average of the transient pulsed current **916**. Transient current **916** peaks as a photoelectron-triggered avalanche occurs in the multiplication region and goes down to a floor as the avalanche event is quenched by a self-quenching process.

FIG. **10** shows a doping profile general for either an embodiment of the present disclosure or a traditional reach-through structure of a GAPD, where the positive and negative values along the *N* coordinates represent p-type and n-type doping concentrations, respectively, and the *x* values along the horizontal axis represent distance (e.g., vertical distance) from the cathode or anode.

In the particular situation of this disclosure, in accordance with the representation of FIG. **10**, the multiplication region goes from distance 0 to distance *L*, while the quenching structure goes from distance *L* to distance *L*+*W*. In the quenching structure, the depleted portion goes from *L* to *L*+*W*₁, while the undepleted portion goes from *L*+*W*₁ to *L*+*W*. On the other hand, in the particular situation of a GAPD, the multiplication region goes from distance 0 to distance *L*, while the reach-through structure goes from distance *L* to distance *L*+*W*.

The following comments and equations will explain the conditions under which, in accordance with the present disclosure, depletion does not occur along the entire length *W* of the quenching structure but only along a distance *W*₁<*W* of the quenching structure.

Should the quenching structure be depleted to a distance *L*+*W*₁ due to a bias applied, according to the Poisson Equation, the field strength *E* and potential *V* in the depletion region can be expressed as:

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$$E(x) = \frac{e^2}{\epsilon_0 \epsilon_{Si}} \int_x^{L+W1} N(x) dx \quad (1)$$

and

$$V(x) = \int_x^{L+W1} E(x) dx \quad (2)$$

where e is the electron charge, and ϵ_0 and ϵ_{Si} are the vacuum and semiconductor permittivities, respectively.

In a simplified situation, where $N_{P0}=0$, the field and potential in the $X < L$ region can be expressed as

$$E(x < L) = \frac{e^2 N_P W1}{\epsilon_0 \epsilon_{Si}} \quad (3)$$

and

$$V(x < L) = \frac{e^2 N_P W1}{\epsilon_0 \epsilon_{Si}} \left(L - x + \frac{W1}{2} \right) \quad (4)$$

Equation (3) shows that the field in the multiplication region will become a constant in the simplified situation. In the particular situation of a GAPD, where the depletion region reaches to the far edge of the p-type doping structure, which is known as “reach through” status, Equation (3) turns into

$$E = \frac{e^2 N_P W}{\epsilon_0 \epsilon_{Si}} \quad (5)$$

There is an electrical field E_{MAX} in each semiconductor beyond which breakdown will occur due to avalanche or sustainable carrier multiplication. In silicon, E_{MAX} is around 10⁶V/cm.

In a traditional reach-through avalanche photodiode, the depletion region has to “reach through” the p-type doping structure and deeply penetrate into the absorption region for the purpose of photoelectron collection before occurrence of the avalanche or breakdown in the multiplication region. Therefore, in a reach-through APD, breakdown or avalanche must not occur earlier. Therefore, a reach-through APD must have

$$N_P W < \frac{\epsilon_0 \epsilon_{Si} E_{MAX}}{e^2} \quad (6)$$

This means that the doping amount ($N_P W$) of a reach-through APD should be well controlled to be below its critical value regulated by E_{MAX} .

On the other hand, in accordance with the present disclosure, breakdown or avalanche is desired to occur in the multiplication region at a low voltage at a moment when the depletion region has not yet attained the far edge of the p-type doping structure. Hence, the doping amount of the p-type doping structure should be selected so that

$$N_P W > \frac{\epsilon_0 \epsilon_{Si} E_{MAX}}{e^2} \quad (7)$$

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In a more general situation where N_{P0} can't be omitted, the device according to the present disclosure can be designed by selecting the doping or doping conditions so that breakdown occurs in the multiplication region before the depletion region reaches the far edge ($L+W$) of the quenching structure.

For example, a more general condition to be respected by devices according to the present disclosure can be summarized as

$$E_{MAX} < \frac{e^2}{\epsilon_0 \epsilon_{Si}} \int_0^{L+W} N(x) dx \quad (8)$$

The term “doping” or “doping conditions” generally indicate doping parameters such as width and doping concentration. In some situations, there may be some other parameters (e.g., substrate background doping N_{P0}) that also influence the position of the depletion boundary.

According to an embodiment of the present disclosure, the quenching structures can have a doping concentration of $(1-2) \times 10^{18}/\text{cm}^3$ and a width of 0.1-0.3 μm . By contrast, a reach-through structure may have a doping concentration of $1 \times 10^{17}/\text{cm}^3$ or below and a width of 0.1-0.2 μm .

The foregoing Detailed Description of exemplary and preferred embodiments is presented for purposes of illustration and disclosure in accordance with the requirements of the law. It is not intended to be exhaustive nor to limit the invention to the precise form or forms described, but only to enable others skilled in the art to understand how the invention may be suited for a particular use or implementation. The possibility of modifications and variations will be apparent to practitioners skilled in the art. No limitation is intended by the description of exemplary embodiments which may have included tolerances, feature dimensions, specific operating conditions, engineering specifications, or the like, and which may vary between implementations or with changes to the state of the art, and no limitation should be implied therefrom.

This disclosure has been made with respect to the current state of the art, but also contemplates advancements and that adaptations in the future may take into consideration of those advancements, namely in accordance with the then current state of the art. It is intended that the scope of the invention be defined by the Claims as written and equivalents as applicable.

Reference to a claim element in the singular is not intended to mean “one and only one” unless explicitly so stated. Moreover, no element, component, nor method or process step in this disclosure is intended to be dedicated to the public regardless of whether the element, component, or step is explicitly recited in the Claims. No claim element herein is to be construed under the provisions of 35 U.S.C. Sec. 112, sixth paragraph, unless the element is expressly recited using the phrase “means for . . .” and no method or process step herein is to be construed under those provisions unless the method or process step, or steps, are expressly recited using the phrase “comprising step(s) for . . .”

The invention claimed is:

1. A photoelectronic device comprising:

a nanoscale doped semiconductor cathode or anode receiving, during operation of the photoelectronic device, multiplied electrons or holes;

an undoped or unintentionally doped nanoscale semiconductor multiplication region connected with the cathode or anode, the multiplication region hosting carrier avalanche and carrier self-quenching during operation of the device; and

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a nanoscale doped semiconductor quenching structure connected with the multiplication region, the quenching structure comprising a depletion region that undergoes depletion during operation of the device and an undepletion region that remains undepleted during operation of the device.

2. The device of claim 1, further comprising a nanoscale cathode or anode contact to provide ohmic contact to the nanoscale cathode or anode.

3. The device of claim 2, wherein the nanoscale cathode or anode contact has a thickness in a 50-200 nm range.

4. The device of claim 2, wherein the nanoscale cathode or anode contact is an amorphous or polycrystalline semiconductor layer.

5. The device of claim 2, wherein the quenching structure has a thickness in a 100-500 nm range.

6. The device of claim 2, assembled in a pillar structure.

7. The device of claim 6, wherein the pillar structure is a horizontal or vertical pillar structure.

8. The device of claim 6, wherein the pillar structure has a length in a 300-1,500 nm range and a diameter in a 1-2,000 nm range.

9. The device of claim 1, wherein the nanoscale cathode or anode has a thickness in a 50-200 nm range.

10. The device of claim 1, wherein the multiplication region has a thickness in a 100-500 nm range.

11. The device of claim 1, wherein, during operation of the device, the multiplication region enters breakdown at a voltage of 10V.

12. The device of claim 1, wherein the nanoscale doped semiconductor cathode or anode is doped with a first type of dopant and the nanoscale doped semiconductor quenching structure is doped with a second type of dopant.

13. The device of claim 1, wherein the undepletion region of the quenching structure acts as a potential well to retard movement of carriers generated during avalanche during operation of the device, thus also quenching the avalanche.

14. The device of claim 6, further comprising a floating cathode or anode arranged on a shoulder region of the pillar structure.

15. The device of claim 1, further comprising a photoelectron absorption region connected with the quenching structure, the device acting, during operation, as a photon detector.

16. The device of claim 1, further comprising a doped semiconductor contact associated with the quenching struc-

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ture, the contact serving as an inlet for carriers coming from other devices, the device acting, during operation, as a single carrier multiplier.

17. An avalanche and self-quenching process for a photoelectronic device, comprising:

providing a nanoscale multiplication region and a nanoscale quenching region connected with the nanoscale multiplication region, the nanoscale quenching region comprising a depletion layer that undergoes depletion during the avalanche self-quenching process, and an undepletion layer that remains undepleted during the avalanche self-quenching process; and

injecting a photoelectron or a photogenerated hole into the nanoscale multiplication region, whereby avalanche is initiated upon the injecting and pairs of free carriers are generated as a result of carrier multiplication, wherein space charge initially contributed by the depletion layer of the nanoscale quenching region is modulated as multiplied carriers of one type move through the nanoscale quenching structure,

and electrical field in the multiplication region is reduced as a result of the modulation, thus quenching the avalanche.

18. The process of claim 17, wherein during avalanche and before quenching the carriers flow across the quenching region towards an anode or a cathode.

19. A photoelectronic device comprising:

a nanoscale doped semiconductor cathode or anode receiving, during operation of the photoelectronic device, multiplied electrons or holes;

an undoped or unintentionally doped nanoscale semiconductor multiplication region connected with the cathode or anode, the multiplication region hosting carrier avalanche and carrier self-quenching during operation of the device; and

a nanoscale doped semiconductor quenching structure connected with and contacted with the multiplication region, the quenching structure comprising a depletion region that undergoes depletion during operation of the device and an undepletion region that remains undepleted during operation of the device.

20. The device of claim 19, wherein the undepletion region of the quenching structure acts as a potential well to retard movement of carriers generated during avalanche during operation of the device, thus also quenching the avalanche.

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